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CP VIOLATION BY SOFT SUPERSYMMETRY BREAKING TERMS IN ORBIFOLD COMPACTIFICATIONS

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ABSTRACT

The possibility of spontaneous breaking of CP symmetry by the expectation values of orbifold moduli is investigated with particular reference to CP violating phases in soft supersymmetry breaking terms. The effect of different mechanisms for stabilizing the dilaton and the form of the non-perturbative superpotential on the existence and size of these phases is studied. Non-perturbative superpotentials involving the absolute modular invariant $j(T)$, such as may arise from $F-$ theory compactifications, are considered.

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String theory may provide a new perspective on the longstanding question of the origin of CP violation. It has been argued [1] that there is no explicit CP symmetry breaking in string theory whether perturbative or non-perturbative. However, CP violation might arise from complex expectation values of moduli or other scalars [1]-[4]. In all supergravity theories, including those derived from string theory, there is the possibility of CP violating phases in the soft supersymmetry- breaking A and B terms and gaugino masses which are in addition to a possible phase in the Kobayashi-Maskawa matrix and the θ parameter of QCD. (See for example, [5] and references therein.) In compactifications of string theory, soft supersymmetry breaking terms can be functions of moduli such as those associated with the radius and angles characterizing the underlying torus of the orbifold compactification. Then, if these moduli develop complex vacuum expectation values, this can be fed through to the low energy supergravity as CP violating phases.

Any nonzero value for d_n, the neutron electric dipole moment, is an indication of CP violation. In principle, complex soft superymmetry-breaking terms in SUSY theories and their resulting phases can lead to large contributions to d_n. These phases are constrained by experiment to be $\leq O(10^{-3})$. It is therefore a serious challenge for SUSY theories to explain why these phases are so small, i.e. why soft susy breaking terms preserve CP to such a high degree. As we will show below, string supersymmetric theories relate the required smallness of CP phases to properties of modular functions.

To estimate the size of such CP violating phases for orbifold compactifications, it is first necessary to minimize the effective potential to determine the expectation values of the T moduli. Such calculations may be sensitive to the solution proposed to the problem of stabilizing the dilaton expectation value. In an earlier paper [4] in the context of orbifolds with broken $PSL(2,Z)$ modular symmetry and a single gaugino condensate non-perturbative superpotential, no assumption was made as to the mechanism for dilaton stabilization. Instead, the dilaton expectation value S and the corresponding auxiliary F_S were treated as free parameters but with ReS fixed to about 2, in line with the value of the inverse gauge coupling constant squared at the string scale. Here, we improve on such calculations by assuming that the dilaton is stabilized either by a multiple gaugino condensate [6], or by stringy non-perturbative corrections to the dilaton Kähler potential. For simplicity, our treatment here is restricted to a single overall modulus T and unbroken $PSL(2,Z)$ modular symmetry. Models with broken modular symmetries will be discussed elsewhere [9]. The calculations are carried out both when the non-perturbative superpotential has the generic form derived from gaugino condensation [10] including the Dedekind function $\eta(T)$, and when the superpotential also involves [11] the absolute modular invariant $j(T)$. Non-perturbative superpotentials involving $j(T)$ may, in principle, arise from orbifold theories containing gauge non-singlet states which become massless at some special values of the moduli [11] (though examples are lacking.) They may also arise from $F-$ theory compactifications [12].

If we assume that the stabilization of the dilaton expectation value at a minimum with a realistic value of ReS is due to a multiple gaugino condensate [6] (includ-

ing hidden sector matter), the general form of the non-perturbative superpotential for a single overall modulus T is of the form

$$W_{np} = \sum_a h_a e^{(\frac{24\pi^2 S}{b_a})} (\eta(T))^{-6(1-\frac{8\pi^2}{b_a}\tilde{\delta}_{GS})} \tag{1}$$

for some coefficients h_a, where the sum over a is over factors in the hidden sector gauge group, the b_a are the corresponding renormalization group coefficients, and the Green-Schwarz coefficient $\tilde{\delta}_{GS}$ is normalized such that the dilaton and moduli dependent Kähler potential is

$$K = -3\log(T + \bar{T}) - \log y \tag{2}$$

with

$$y = S + \bar{S} - \tilde{\delta}_{GS} \log(T + \bar{T}) \tag{3}$$

Since we do not wish to commit ourselves to any particular choice of gaugino condensates nor of hidden sector matter, we find it convenient to rewrite (1) in the form

$$W_{np} = \Omega(\Sigma)\eta(T)^{-6} \tag{4}$$

where

$$\Sigma = S + 2\tilde{\delta}_{GS} \log \eta(T) \tag{5}$$

and

$$\Omega(\Sigma) = \sum_a h_a e^{\frac{24\pi^2}{b_a}\Sigma} \tag{6}$$

In what follows, we shall treat Σ as a parameter to be chosen so that y is approximately 4, and we shall also treat

$$\rho \equiv \frac{\frac{d\Omega}{d\Sigma}}{\Omega} \tag{7}$$

as a free parameter. The parameter ρ is related to the dilaton auxiliary field F_S by

$$\rho = \frac{1 - F_S}{y} \tag{8}$$

If instead we assume that stabilization of the dilaton expectation value is produced by stringy non-perturbative corrections [8] to the dilaton Kähler potential, then we write the dilaton and moduli dependent part of the Kähler potential as

$$K = -3\log(T + \bar{T}) + P(y) \tag{9}$$

where $P(y)$ is a function to be determined by non-perturbative string effects. In that case, we shall treat $\frac{dP}{dy}$ and $\frac{d^2P}{dy^2}$, which we shall see occur in the effective potential and the soft supersymmetry breaking terms, as free parameters.

The form of the effective potential which encompasses both possibilities is

$$\begin{aligned} V_{eff} &= |W_{np}|^2 \, e^{P(y)} \, (T+\bar{T})^{-3} \\ &\times \Big[-3 + \Big|\frac{dP}{dy} + \rho\Big|^2 \Big(\frac{d^2P}{dy^2}\Big)^{-1} + \frac{|\tilde{\delta}_{GS}\rho - 3|^2}{(3+\tilde{\delta}_{GS}\frac{dP}{dy})} (T+\bar{T})^2 |\hat{G}(T,\bar{T})|^2 \Big] \end{aligned} \tag{10}$$

where

$$\hat{G}(T,\bar{T}) = (T+\bar{T})^{-1} + 2\eta^{-1}\frac{d\eta}{dT} \tag{11}$$

and ρ has the value $\frac{24\pi^2}{b}$ for the single condensate case. The soft supersymmetry-breaking terms may be calculated by standard methods. (See for example [13] and [14], from which the earlier literature can be traced.) The gaugino masses M_a are given by

$$\begin{aligned} M_a &= m_{3/2}(Ref_a)^{-1} \times \Big[\frac{\partial \bar{f}_a}{\partial \bar{S}} \Big(\frac{d^2P}{dy^2}\Big)^{-1} \Big(\frac{dP}{dy} + \rho\Big) \\ &+ \Big(\frac{b'_a}{8\pi^2} - \tilde{\delta}_{GS}\Big)\Big(1 + \frac{\tilde{\delta}_{GS}\frac{dP}{dy}}{3}\Big)^{-1} \Big(\rho\frac{\tilde{\delta}_{GS}}{3} - 1\Big)(T+\bar{T})^2|\hat{G}|^2 \Big] \end{aligned} \tag{12}$$

where b'_a is the usual coefficient occuring in the string loop threshold corrections to the gauge coupling constant [13, 15]. Provided the dilaton auxiliary field F_S in (12) is real, there are no CP violating phases in the gaugino masses. The soft supersymmetry-breaking terms are given by

$$\begin{aligned} m_{3/2}^{-1} A_{\alpha\beta\gamma} &= \Big(\frac{d^2P}{dy^2}\Big)^{-1}\Big(\frac{dP}{dy} + \rho\Big)\frac{dP}{dy} \\ &+ \Big(1 + \frac{\tilde{\delta}_{GS}}{3}\frac{dP}{dy}\Big)^{-1}\Big(1 - \rho\frac{\tilde{\delta}_{GS}}{3}\Big)(T+\bar{T})\bar{\hat{G}} \\ &\times \Big(3 + n_\alpha + n_\beta + n_\gamma - (T+\bar{T})\frac{\partial \log h_{\alpha\beta\gamma}}{\partial T}\Big) \end{aligned} \tag{13}$$

where the superpotential term for the Yukawa couplings of ϕ_α, ϕ_β and ϕ_γ is $h_{\alpha\beta\gamma}\phi_\alpha\phi_\beta\phi_\gamma$, the modular weights of these states are n_α, n_β and n_γ, and the usual rescaling by a factor $\frac{W_{np}}{|W_{np}|}$ required to get from the supergravity theory derived from the orbifold compactification of the superstring theory to the spontaneously broken globally supersymmetric theory has been carried out. (See, for example, [3].) The $\frac{\partial \log h_{\alpha\beta\gamma}}{\partial T}$ contribution to (13) is essential for the modular invariance of $A_{\alpha\beta\gamma}$ and can make a significant contribution to any CP violating phase. For illustrative purposes we have taken $h_{\alpha\beta\gamma}$ to be of the form encountered [16] when each of the states ϕ_α, ϕ_β and ϕ_γ is in the particular twisted sector of the $Z_3 \times Z_6$ orbifold with the same twisted boundary conditions as the twisted sector of the Z_3 orbifold. This is an appropriate choice because the $Z_3 \times Z_6$ orbifold has three $N=2$ moduli, $T_i, \ i=1,2,3$, so that the model of a single overall modulus $T = T_1 = T_2 = T_3$ is consistent. In this case,

if we arrange $h_{\alpha\beta\gamma}$ to be covariant under the $T \to \frac{1}{T}$ modular transformation, it is a product of 3 factors, one for each complex plane,of the form

$$h(T_i, k_i = 0) + (\pm\sqrt{3} - 1)h(T_i, k_i = 1) \tag{14}$$

where

$$h(T_i, k_i) \sim e^{-\frac{2}{3}\pi k_i^2 T_i}\Big[\Theta_3(ik_iT_i, 2iT_i)\Theta_3(ik_iT_i, 6iT_i) + \Theta_2(ik_iT_i, 2iT_i)\Theta_2(ik_iT_i, 6iT_i)\Big] \tag{15}$$

Each of the modular weights n_α, n_β and n_γ has the value -2.

The expression for the soft supersymmetry-breaking B term depends on the mechanism adopted for generating the μ term for the Higgs scalars H_1 and H_2, with corresponding superfields ϕ_1 and ϕ_2. If we assume that the μ term is generated non-perturbatively as an explicit superpotential term $\mu_W \phi_1 \phi_2$, then the B term, which in this case we denote by B_W, is given by

$$\begin{aligned} m_{3/2}^{-1} B_W &= -1 + \Big(\frac{d^2P}{dy^2}\Big)^{-1}\Big(\frac{dP}{dy} + \bar{\rho}\Big)\Big(\frac{dP}{dy} + \frac{\partial \log \mu_W}{\partial S}\Big) \\ &+ \Big(1 + \frac{\tilde{\delta}_{GS}}{3}\frac{dP}{dy}\Big)^{-1}\Big(1 - \bar{\rho}\frac{\tilde{\delta}_{GS}}{3}\Big)(T + \bar{T})\bar{\hat{G}} \\ &\times \Big(3 + n_1 + n_2 - (T + \bar{T})\frac{\partial \log \mu_W}{\partial T} - \tilde{\delta}_{GS}\frac{\partial \log \mu_W}{\partial S}\Big) \end{aligned} \tag{16}$$

where n_1 and n_2 are the modular weights of the Higgs scalar superfields ϕ_1 and ϕ_2, and again the appropriate rescaling has been carried out.

On the other hand, if the μ term is generated by a term of the form $Z\phi_1\phi_2$+h.c. in the Kähler potential mixing the Higgs superfields [17], then (before rescaling the Lagrangian) the B term, which we denote by B_Z in this case, is given by

$$\begin{aligned} -\, m_{3/2}^{-1}\mu_Z^{eff} B_Z &= W_{np} Z \times \Bigg[2 + \Big(\frac{T + \bar{T}}{3 + \tilde{\delta}_{GS}\frac{dP}{dy}}(\tilde{\delta}_{GS}\rho - 3)\hat{G}(T, \bar{T}) + \text{h.c.}\Big)\Bigg] \\ &+ W_{np} Z \times \Big[-3 + \Big|\frac{dP}{dy} + \rho\Big|^2\Big(\frac{d^2P}{dy^2}\Big)^{-1} \\ &+ \frac{|\tilde{\delta}_{GS}\rho - 3|^2 (T + \bar{T})^2}{(3 + \tilde{\delta}_{GS}\frac{dP}{dy})}|\hat{G}(T, \bar{T})|^2\Big] \end{aligned} \tag{17}$$

and the effective μ term in the superpotential has $\mu = \mu_Z^{eff}$ where

$$\mu_Z^{eff} = |W_{np}| Z\Big(1 - \frac{\tilde{\delta}_{GS}}{3}\rho + \frac{T + \bar{T}}{3}(\tilde{\delta}_{GS}\rho - 3)\hat{G}(T, \bar{T})\Big) \tag{18}$$

To obtain the final form for B_Z in the low energy supersymmetry theory, rescaling of the Lagrangian by $\frac{W_{np}}{|W_{np}|}$ has to be carried out. In that case, any CP violating phase

derives from (18). This mechanism requires [17] that the Higgs scalars are in the untwisted sector of the orbifold and are associated with the T and U modulus for a complex plane on which the point group acts as Z_2. In the spirit of retaining only a single overall T modulus the auxiliary field of the U modulus has been set to zero in deriving (17) ans (18), which is equivalent to assuming that the supersymmetry breaking is dominated by the dilaton and the T modulus.

In the case of multiple gaugino condensate with perturbative Kähler potential, minimization of the effective potential at fixed Σ for different real values of the parameter ρ with Re S taken to be about 2 leads to the following conclusions. It can be seen analytically that the fixed points of $PSL(2,Z)$ at $T=1$ and $T=e^{\frac{i\pi}{6}}$, at which $\hat{G}(T,\bar{T})$ is zero, are always extrema (even for $\tilde{\delta}_{GS}\neq 0$.) For $0.1 \leq \rho \leq 0.4$, the minimum is at a real value of T which approaches 1 as ρ approaches 0.42. For $0.42 \leq \rho \leq 0.75$, T remains at the fixed point at $T=1$, and for $\rho \geq 0.8$ the minimum is at the other fixed (See fig.1) point at $T=e^{\frac{i\pi}{6}}$. (There are of course also minima at points obtained from these minima by modular transformations.) This resembles what happens for a single condensate but treating the dilaton auxiliary field F_S as a free parameter to simulate dynamics stabilizing the dilaton expectation value [18].

Gaugino condensate models (with perturbative Kähler potential) in general have negative vacuum energy at the minimum. However, as other authors have emphasized [18], the solution to the vanishing cosmological constant problem is probably in the realm of quantum gravity and, as the present type of discussion treats gravity classically, we need not necessarily impose vanishing vacuum energy as a constraint on the theory. On the other hand, if we do arrange for zero vacuum energy by introducing an extra matter field which does not mix with the dilaton and moduli fields [3], then the effect in the minimization of the effective potential with respect to T is that the factor premultiplying the bracket in (10) is not to be differentiated. Then, for $0.25 \leq \rho \leq 2.15$ minima occur at the fixed points at $T=1$ and $T=e^{\frac{i\pi}{6}}$. For $\rho \geq 2.2$ there is a single real minimum.

In the case of a single gaugino condensate, but with the dilaton expectation value being stabilized by stringy non-perturbative corrections to the dilaton Kähler potential, minimization of the effective potential with y fixed at 4 for different values of the parameters $\frac{dP}{dy}$ and $\frac{d^2P}{dy^2}$ leads instead to the following outcome. For a wide range of choices of these parameters T is either at a fixed point value or it is real. However, for some choices of the parameters T takes complex values which differ from the fixed point value $e^{\frac{i\pi}{6}}$. For example, for $\frac{dP}{dy}=-11/4$ and $\frac{d^2P}{dy^2}=-1.3$, one obtains

$$T|_{min} = 5.234339 + 0.0009575i \tag{19}$$

and the potential is very flat.

The consequences of these values of the modulus T at the minimum for possible CP violating phases in the soft supersymmetry-breaking terms are rather striking. It might have been thought *a priori* that when T is at a fixed point at $e^{\frac{i\pi}{6}}$ a CP violating phase of order 10^{-1} might be induced. However, as has been observed earlier [4], if T is precisely at a fixed point value, and so at a zero of $\hat{G}(T,\bar{T})$, the CP

violating phase vanishes identically, as can be seen from (13)- (18). Thus, for the case where the dilaton is stabilized by a multiple gaugino condensate with perturbative Kähler potential, there are no CP violating phases in the soft supersymmetry breaking terms. In the case of a single gaugino condensate with the dilaton stabilized by non-perturbative corrections to the dilaton Kähler potential, the conclusion is the same for a wide range of values of $\frac{dP}{dy}$ and $\frac{d^2P}{dy^2}$. However, in this case, it is possible at the minimum for T to be at a complex value away from the fixed point as, for example, in (19). At first sight, it appears that there might then be a CP violating phase of order 10^{-4}. However, the CP violating phases are far smaller than this (of order 10^{-15} for T as in (19).) The reason for this is the very rapid variation of the imaginary part of $\hat{G}(T,\bar{T})$ with ReT as Re T moves away from 1 if Im T is held fixed. The imaginary part of $\hat{G}(T,\bar{T})$ varies by 11 orders of magnitude as Re T goes from $\frac{\sqrt{3}}{2}$ to 5.0 (See fig.2). The possibility of suppressing CP violating phases in this way has been suggested earlier [4] in the context of orbifold models with broken $PSL(2,Z)$ modular symmetries.

If, as discussed in the introduction, we allow the possibility that the non-perturbative superpotential W_{np} may involve the absolute modular invariant $j(T)$, as well as the Dedekind eta function [11], then the situation is very different. Then W_{np} contains an extra factor $H(T)$ where the most general form of $H(T)$ to avoid singularities inside the fundamental domain [11] is

$$H(T) = (j - 1728)^{m/2} j^{n/3} P(j) \tag{20}$$

where m and n are integers and $P(j)$ is a polynomial in j. This results in modification of (10) and (13)-(18) by the replacement of $(\tilde{\delta}_{GS}\,\rho-3)\hat{G}(T,\bar{T})$ by $(\tilde{\delta}_{GS}\,\rho-3)\hat{G}(T,\bar{T})+\frac{dlnH}{dT}$. It is then possible, for some choices of H, to obtain (complex) minima of the effective potential for T that lead to CP violating phases in the soft supersymmetry breaking terms of order $10^{-4} - 10^{-1}$. Let us start with the case of stabilizing the dilaton by multiple gaugino condensate, then for $P(j) = 1$ and $m = n = 1$, $\tilde{\delta}_{GS} = -\frac{30}{8\pi^2}$, $\rho = 0.45$, we find that the minimum is on the unit circle at

$$T|_{min} = 0.971353713 \pm 0.2376383050i \tag{21}$$

For the Yukawa couplings which we have considered (see below), this leads to a CP violating phase not greater than 10^{-4}. Also for $P(j) = 1$ and $m = n = 1$, $\tilde{\delta}_{GS} = -\frac{50}{8\pi^2}$, $\rho = 0.26$ the minimum is also on the unit circle at

$$T|_{min} = 0.971352323 \pm 0.237643985i \tag{22}$$

which again leads to CP violating phase not greater than 10^{-4} in the A term. On the other hand, if we assume that the dilaton is stabilized by non-perturbative corrections to the Kähler potential, then it is possible to find minima of the effective potential at complex values of the $T-$ modulus not only on the boundary of the fundamental domain *but also inside the fundamental domain*. In this case larger CP violating phases arise. Indeed, it is possible for some values of the parameters $\frac{dP}{dy}$ and $\frac{d^2P}{dy^2}$

to obtain phases that exceed the current experimental limit. As a result we can constrain our non-perturbative parameter space. For instance, for $\frac{dP}{dy} = -1.5$ and $\frac{d^2P}{dy^2} = -0.2,\ m = 1, n = 3, \delta_{GS} = -30$ we obtain the following solutions:

$$T|_{min} = 1.01196232 + 0.16800043\, i \tag{23}$$

and its $T - dual$ under the generator $T \rightarrow \frac{1}{T}$,

$$T|_{min} = 0.96167455 - 0.15965193\, i \tag{24}$$

Both minima lead to a phase $\phi(A)$ of order 10^{-2}. The foregoing results need a little amplification. For minima connected by $T \rightarrow T + i$ the Yukawa $h_{\alpha\beta\gamma} = h(T, k = 0)$ leads to the same CP violating phases at both minima, while for minima connected by $T \rightarrow \frac{1}{T}$ the Yukawa $h_{\alpha\beta\gamma} = h(T, k = 0) + (\sqrt{3} - 1)h(T, k = 1)$, which transforms as $h_{\alpha\beta\gamma}(1/T) = T h_{\alpha\beta\gamma}(T)$, also leads to the same CP violating phases at both minima. Both are of order 10^{-2}. However, since there is no linear combination of Yukawas which has modular weight 1 with respect to *all* modular transformations, we cannot do better than characterize the scale of the CP violating phases in this way. It is important to note that since V_{eff} is modular invariant, the calculation of the electric dipole moment of the neutron, for example, will necessarily yield a modular invariant result, presumably with magnitude characteristic of the order 10^{-2} scale of the CP violating phase of $A_{\alpha\beta\gamma}$. This calculation will necessarily entail contributions from more than one A term.

Similarly, for $\frac{dP}{dy} = -1.4,\ \frac{d^2P}{dy^2} = -0.1,\ m = 1, n = 3, \delta_{GS} = -30$, see fig.3, we obtain

$$T|_{min} = 0.79314323 + 0.11307387\, i \tag{25}$$

its $T - dual$ under $T \rightarrow \frac{1}{T}$

$$T|_{min} = 1.23569142 - 0.17616545\, i \tag{26}$$

as well as the $T - dual$ of the later under $T \rightarrow T + i$

$$T|_{min} = 1.23569142 + 0.82383457\, i \tag{27}$$

At the above 3-points of the moduli space we obtain a phase $\phi(A)$ of order 10^{-3}–10^{-2}.

In conclusion, whether the dilaton expectation value is stabilized by a multiple gaugino condensate or by stringy corrections to the dilaton Kähler potential, we have found that, provided the superpotential does not contain the absolute modular invariant $j(T)$, the CP violating phases in the soft supersymmetry-breaking terms are either zero or much smaller than 10^{-3}. Zero phases occur when the minimum for the modulus T is at a zero of $\hat{G}(T, \bar{T})$ or is real. Phases much smaller than 10^{-3} occur when T is at a complex value with the real part of T far from its value at a zero of $\hat{G}(T, \bar{T})$, because of the rapid variation of the imaginary part of $\hat{G}(T, \bar{T})$ as $Re\ T$ varies. However, if we allow the more general possibility that W_{np} involves

$j(T)$ as well as $\eta(T)$, as may arise from orbifold theories if the theory contains gauge non-singlet states that are zero at some special values of the moduli [11], or may arise from $F-$ theory compactifications [12], then it is possible in some models to obtain CP violating phases in the soft supersymmetry-breaking terms of order $10^{-4} - 10^{-1}$. The largest phases occur for minima of the potential inside the fundamental domain of the $PSL(2, Z)$ $T-$ modulus.

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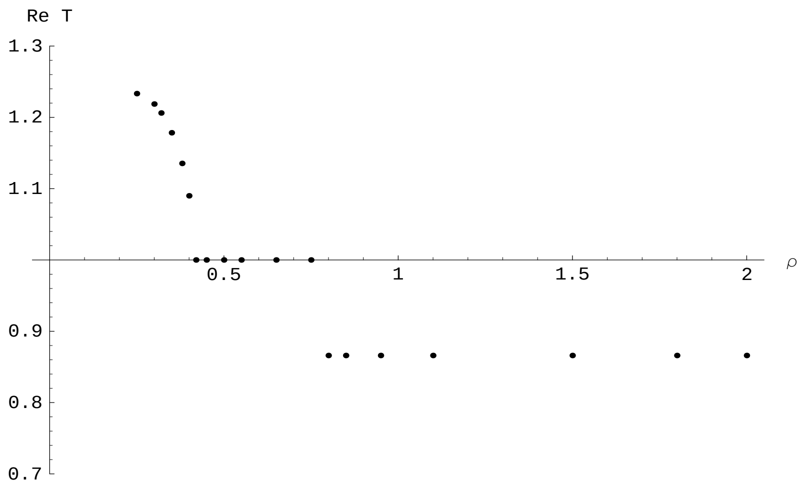

Figure 1: Variation of ReT at the minimum of V_{eff} with ρ, defined in eqn.(8), in multiple gaugino condensate models.

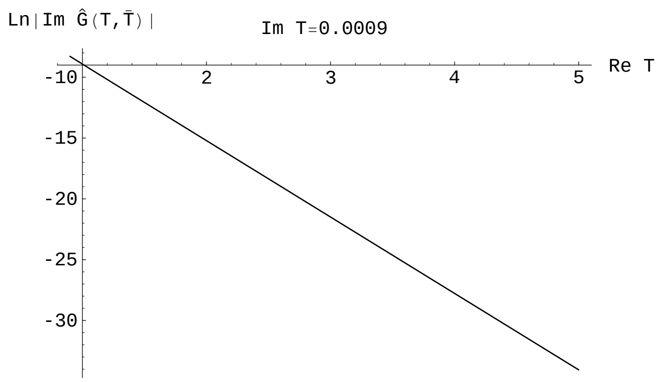

Figure 2: Variation of the logarithm of $Im\hat{G}$ with respect to ReT.

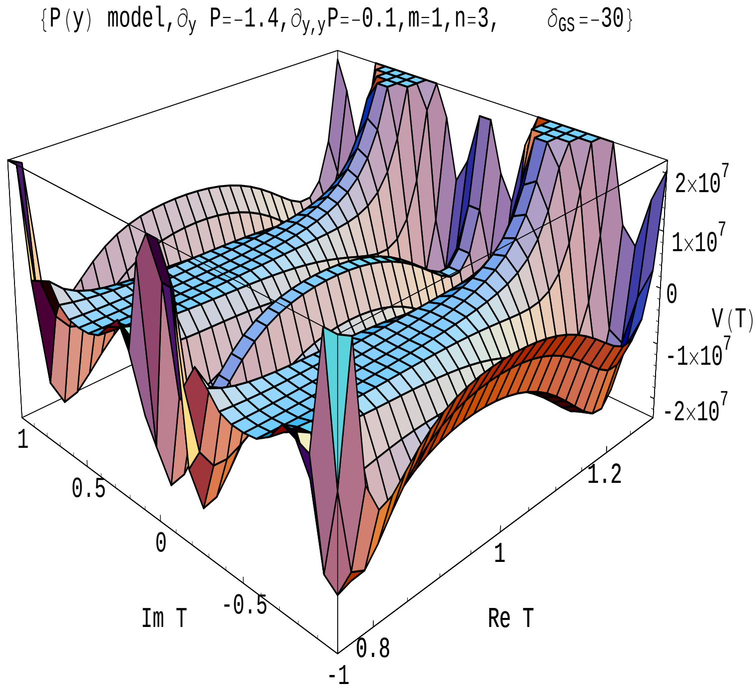

Figure 3: The effective potential for the non-perturbative dilaton Kähler potential with the parameters as defined in the text.